

UDC 534.86:
621.376.56



RESEARCH DEPARTMENT



REPORT

**Pulse code modulation for high-quality sound signal distribution:
simulation of an advanced form of error protection**

No. 1971/37

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**PULSE CODE MODULATION FOR HIGH-QUALITY SOUND SIGNAL DISTRIBUTION:
SIMULATION OF AN ADVANCED FORM OF ERROR PROTECTION**

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Work covered by this report was undertaken by the BBC Research Department for the BBC and the ITA

M.G. Croll, B.Sc.(Hons.), A.R.C.S.


Head of Research Department

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PULSE CODE MODULATION FOR HIGH-QUALITY SOUND SIGNAL DISTRIBUTION: SIMULATION OF AN ADVANCED FORM OF ERROR PROTECTION

Summary

This report describes an advanced form of error protection which is applicable to p.c.m. multiplexed sound signals and can be used to reduce the audible effect of errors introduced when the digital signal is transmitted through a communications system. The method of error detection, in which single-bit parity checks are made of both the words and digits, enables single-bit errors within a frame to be corrected digitally. Most errors affecting more than one bit can be detected but because the digits effected cannot be uniquely located, concealment processes are applied to the erroneous words.

An experimental simulation of the advanced system showed that when it was used in conjunction with an interpolator that conceals errors which are detected but not corrected, the subjective impairment of the sound signal would be 'Just Perceptible' when the error rate is 1 in 1000 bits.

1. Introduction

When a p.c.m. signal is transmitted through a communications circuit some digits may be incorrectly detected at the receiving terminal through the presence of noise or distortion in the received signal. If the digital signals thus detected are decoded and applied to a loudspeaker, errors occurring in the more significant digits produce very loud clicks which are distracting if they occur frequently. In such circumstances it is normal to provide some means of reducing the signal impairment caused by errors.

Digital errors can be detected by the use of parity digits which are generated from the digital signal and added to it before transmission. At the receiving terminal the signal is processed to check its parity against the parity digits that were added to it. If parity is applied in this way simultaneously to all the digits in a frame of a multiplex p.c.m. signal* it is possible to determine whether errors have been introduced into that frame, but the words or bits affected cannot be identified, so that if that frame is declared erroneous, some action must be taken at the output of all channels to avoid any errors being passed. However, it has been found preferable to apply separate parity checks to each word so that the remedial action is applied only to the audio channels which are affected by

errors. A system using this principle, in which single-bit parity checks are applied to the five most significant digits of each word has been found to reduce the subjective effect of errors by up to one and a half grades on a six-point scale.¹

Described in this report is an advanced form of signal protection based on a system used in computer technology and known as 'iterated parity'.² In this system the digits to be protected are formed up in blocks and checking is applied separately to each row and column of the block. Hence the position of a single error can be uniquely located from its 'map reference' and can be corrected digitally by inverting the erroneous bit. In the present application a convenient block of digits consists of one frame of the p.c.m. multiplex signal, and the digital words, each relating to a sample of the audio signal from a different channel, form successive rows.

In this work the effect of such a system of protection was calculated and then experimentally simulated so that its performance could be compared subjectively with that of simpler error protection systems.

2. The error corrector

2.1 Error checking

Error detection is effected by means of two sets of single-bit parity checks applied to all digits to be protected.

*In this report a multiplexed system is taken as one in which a digital word describes one sample of an audio signal and a particular word position in each frame is dedicated to a particular audio signal.

The operation of the system is shown diagrammatically in Fig. 1, where a matrix is used to represent these digits in one frame of a 13-channel multiplex p.c.m. system. Each channel word forms one row of the matrix with the most significant digits forming the left-hand column. Parity digits q, each generated from a different channel word, are shown in the figure as the right-hand column of the matrix; parity digits p, each generated from a different column – including the column of q check digits – are shown as the bottom row of the matrix. In a practical p.c.m. multiplex system the q check digits could each be appended to the relevant channel word while the p check digits could be stored and transmitted together at the end of the frame as an additional digital word.

2.2 Correction of single error in the frame

If a single error occurs, then the channel affected will be indicated by one of the q check digits, while the position of the erroneous digit in that word will be indicated by one of the p check digits. Hence the error is located, and, as a binary code is used, it can be corrected by inverting the faulty digit, i.e. changing 0 to 1 or 1 to 0 as the case may be.

2.3 Detection of multiple errors in the frame

The bit position of more than one error in each frame cannot be uniquely located. For example, two errors which are not in the same row or column will be indicated by two p checks and two q checks in such a way that four

different locations are suspect. However in this case, the two erroneous words are uniquely defined and some remedial action can be taken to conceal the errors at the outputs of the two channels effected.

In other cases, for example when two errors occur in one channel word, there will be indications that errors have occurred but the channel word effected will not be defined (i.e. there will be two p indications but no q indications of errors because using single-bit parity an even number of errors is not detected). Here concealment, if applied at all, must be applied to all channel words to avoid passing an erroneous word in one channel.

Hence although multiple errors cannot be located and corrected in this system, they will in most cases be detected and their subjective effect can be mitigated using error-concealment techniques.

3. Error-concealment systems

When a channel word is found to be in error and cannot be corrected, that entire word may be replaced, by simply repeating the previous one. This has been found to be an effective means of error concealment but it does leave some residual impairment.¹ A better method of generating the substitute word is by a linear interpolation between the preceding and succeeding words in that channel. The latter method, which involves some form of signal storage, gives a better approximation to the original channel word and produces less residual impairment of the signal.

		DIGIT POSITIONS IN WORD								
		1	2	3	4	5	.....			
Channel Word Positions In Frame	1	1·1	1·2	1·3	1·4	1·5		q ₁	Channel Check Digits	
	2	2·1	2·2	2·3	2·4	2·5	.....	q ₂		
	3	3·1	3·2	3·3	3·4	3·5	.....	q ₃		
	4	4·1	4·2	4·3	4·4	4·5	.....	q ₄		
	5	5·1	5·2	5·3	5·4	5·5	.....	q ₅		
	6	6·1	6·2	6·3	6·4	6·5	.....	q ₆		
	7	7·1	7·2	7·3	7·4	7·5	.....	q ₇		
	8	8·1	8·2	8·3	8·4	8·5	.....	q ₈		
	9	9·1	9·2	9·3	9·4	9·5	.....	q ₉		
	10	10·1	10·2	10·3	10·4	10·5	.....	q ₁₀		
	11	11·1	11·2	11·3	11·4	11·5	.....	q ₁₁		
	12	12·1	12·2	12·3	12·4	12·5	.....	q ₁₂		
	13	13·1	13·2	13·3	13·4	13·5	.....	q ₁₃		
		p ₁	p ₂	p ₃	p ₄	p ₅		p _q		
		Digit significance check digits								

Fig. 1 - The matrix relating check digits to bit positions in a frame

With both methods of concealment the signal impairment produced is less than that caused by an error in one of the more significant digits but greater than an unconcealed error in one of the less significant digits. Hence the number of digits, n , to be protected in each channel word should be chosen such that the concealment process causes a programme impairment which, when averaged over a period, is similar to that caused by errors in the $(n+1)^{\text{th}}$ significant digit. In the error-detection system described in this report, errors are in some cases detected but the channel words affected cannot be identified. In this case it must be decided whether to let the errors pass or apply concealment simultaneously to all channels, thus impairing those which were free from the error. Again it is necessary to consider the average programme impairment for one channel over a period, and compare the average impairment caused by a number of unconcealed errors in more significant digits with that caused by a larger number of operations of the concealment system. Hence the decision will depend on the degree of impairment produced by the particular error concealment process employed, having regard to the ratio of the number of faulty channels to the total and the programme impairment caused by undetected errors in the more significant digits.

4. Calculation of the performance of the error corrector

4.1 General

To enable multiple errors to be detected and concealed with the minimum quality impairment when there is more than one p indication and more than one q indication of errors, two rules have been formulated. These are not unique and the second is based on the premise that it is better to apply concealment to all channels than allow errors to pass in one or more channels.

- If the number of q indications is more than or equal to the number of p indications, then it is likely that the channels indicated by q contain errors, and error concealment can be applied to these channels.
- If the number of p indications is more than the number of q indications, then it is likely that some channels, not individually identifiable, contain multiple errors and concealment should be applied to all channels.

By applying the above rules instead of applying concealment only when indicated by the p check digits, the number of errors which are undetected — and therefore not concealed — is considerably reduced, and although the concealment system operates more often, the overall effect should be better.

4.2 The relative number of concealments and undetected errors in one channel

In the present study the optimum design of error corrector was determined by comparing the performance in conjunction with different concealment systems and when protecting different numbers of digits. Calculations were based on 5, 7 or 9 protected digits per channel in a frame of

13 active channels.

Whether the errors are concealed or allowed to pass depends on the way they occur within the frame. Following the rules shown above, two errors in a frame either cause concealment to be applied to two channel words or to all channel words, depending on whether the errors are in different channels or not. Three errors in a frame may likewise cause concealment to be applied to three or to all channel words. However, two errors might occur in one channel and one in a different channel but affecting a digit of equal significance to either of the first two. In this case it can be seen that errors will be passed undetected in the two channels and an additional error will be created in one of them.

For the purpose of the present investigation, the probability of having a particular number of errors in a frame was calculated, using the binomial formula, for random bit error rates from 1 in 10^4 to 1 in 30. For each of these numbers of errors in the frame, the relative probabilities of the different ways in which the errors can occur were then calculated. Hence, the average rate of concealed errors and of undetected errors in one channel was determined with reference to the two rules shown earlier. The results are shown in Fig. 2 for the three

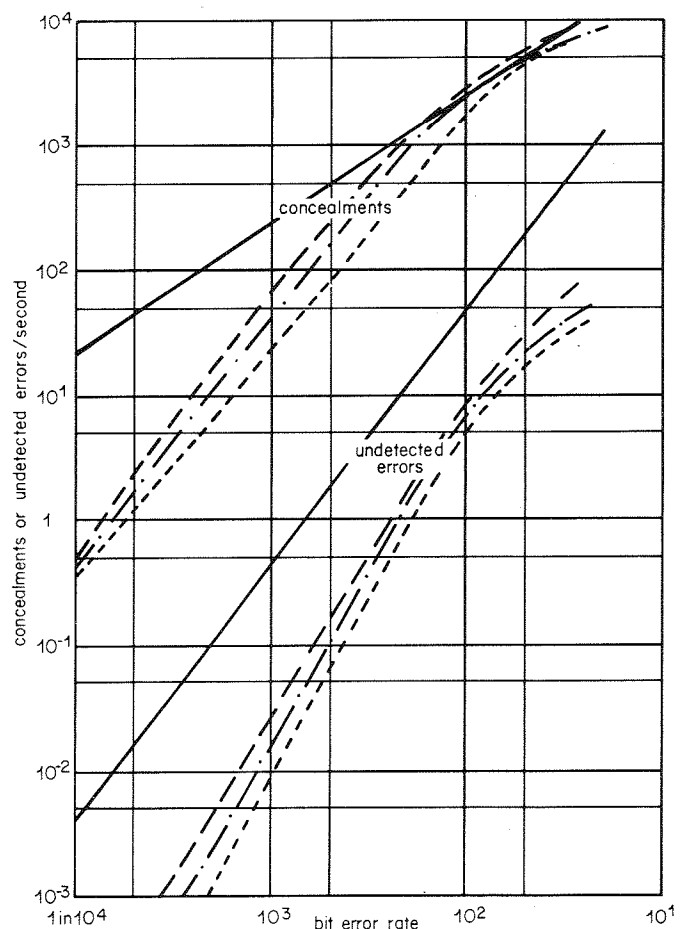


Fig. 2 - Calculated performance of the error corrector

—	Single bit parity	5 bits per word protected
- - -	Error corrector	9 bits per word protected
· · · · ·	Error corrector	7 bits per word protected
- - - - -	Error corrector	5 bits per word protected

numbers of digits to be protected (i.e. 5, 7, 9 per channel word); for comparison, the number of concealments and undetected errors in each channel are also shown for a single parity bit per channel system, where the 5 most significant digits are protected.

5. Simulation of the performance of the error-correcting system

To allow a subjective assessment to be made of the efficacy of the error corrector it was experimentally simulated for one error rate. An error rate of 1 in 1000 was chosen, so that the number of undetected errors would be small and the effect of the system would be to reduce considerably the subjective effect of the remainder. At a higher error rate it would have been necessary to use more complex equipment to simulate the many undetected errors, while at a lower rate the degree of impairment to be expected would be so low as to make subjective evaluation uncertain. For the simulation, use was made of a multiple recording technique based on the principle that different random effects can be added individually.

The programme used was a short recorded excerpt of trumpet music which had been previously found critical for testing error-suppression systems. The test passage was first transmitted through the error-concealment system, which was randomly operated at the appropriate average rate by white noise, and the output was recorded. Next, errors were produced randomly in the lower significance digits of a 13-bit d.a.c. and the decoded output was added to the first recording. Finally, the occasional undetected errors in the protected digits were simulated by using a manually-operated pulse generator. The length of the programme excerpt was 25s and the rates of undetected errors were less than once every 30s, so no more than two undetected errors were added to any excerpt.

Recordings were prepared simulating the following conditions:—

Number of bits protected	Method of concealment
5 } 7 } 9 }	Word repetition
5 } 7 } 9 }	Interpolation between preceding and succeeding samples.

6. Results

The recording described above was listened to by about half a dozen observers and from their conclusions, which were unanimous, several deductions were made. It appeared that when only the five most significant digits of

each channel word were protected, the most distracting effect was caused by the errors in the sixth and seventh digits, and that the total impairment of the signal was almost independent of the method of concealment. However, when seven or nine digits were protected the impairment was much less when interpolation was used; in this case the total impairment of the signal was much the same whether seven or nine digits were protected, so that on grounds of instrumental economy, seven may be regarded as the optimum.

From the simulation it would appear that the optimum design of error corrector would protect only the seven most significant digits and error concealment would be by interpolation. It was also found that with this optimum condition, the degree of impairment for a 1 in 10^3 error rate was about the same as with a single-bit parity system protecting five digits, using word repetition, for a 1 in 10^5 error rate. This impairment was assessed as 'Just Perceptible'.

The simulation process described above involved several generations of recording and the final product has a poor signal-to-noise ratio. It is possible that errors in the lower significance digits may have been masked to some extent by noise. This would not however affect the relative merits of the systems compared.

7. Conclusions

It is difficult to predict how the error-correcting system would perform at error rates higher than those simulated. It can be seen from the curves in Fig. 2 that the number of concealments and the number of undetected errors increases more rapidly than the error rate, but that there will always be fewer undetected errors from the error corrector than from a simple single-bit parity system.

An error corrector of the kind described, protecting the seven most significant digits of each channel word and using interpolation as a means of concealing errors, might enable the p.c.m. multiplex sound signal to be transmitted through communication circuits where random digital errors are produced at average rates up to 1 in 1000 bits. In such circumstances the signal impairment might not be more than 'Just Perceptible'.

8. References

1. PCM Sound Signal Distribution: Protection against Digit Errors. BBC Research Department Report in preparation.
2. PETERSON, W.W. 1968. Error Correcting Codes. Cambridge Mass., M.I.T. Press and Wiley, 1968. p. 81.